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Estimating Decay in Living Trees:

An Assessment of Two Decay Detection Instruments

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An Assessment of Two Decay Detection Instruments

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Abstract

Wood decay causes substantial wood fibre loss in living trees. In Ontario, information on decay and cull is summarized in provincial cull tables developed prior to the 1960s. These data were recently re-analyzed and data gaps were revealed, specifically in overmature stands and boreal mixedwood stands. As well, decay information is scarce for second and third generation forests. To fill these information gaps, a practical, operational data collection method is needed. To address these concerns, we tested 2 decay-detection instruments (the Sibert MicroProbe® [DmP] and the Resistograph® F400 [Resi]) to determine their applicability to Ontario's forests. Decay was measured using the instruments as well as a traditional visual decay assessment method at the cut end of 71 sugar maple (*Acer saccharum* Marsh.) and 60 aspen (*Populus tremuloides* Michx.) logs. Results from both the DmP and the Resi were significantly different than those from the visual method, although actual differences were small. The DmP was faster than the Resi when drilling through soft wood such as aspen, but was not as effective for the harder maple wood. Although slower, the Resi was more versatile as it was able to drill through soft and hard wood, and it was also rugged enough for our forest conditions. Training and experience are necessary to properly operate both instruments and to correctly interpret the resulting electronic data sets.

The DmP and the Resi detect and quantify decay along a single line through a tree or log. Decay estimation models are currently being developed to convert this linear data into decay volume estimates for the sampled trees. Improved tools for non-destructively assessing decay in trees and logs continue to be developed. These tools have many advantages over traditional decay detection systems: they are faster, they produce an electronic database, and they allow trees to be re-measured to follow decay progression through time. These devices could be a valuable asset to future decay data collection efforts.

Résumé

La pourriture entraîne une perte substantielle de la fibre ligneuse dans les bois vifs. En Ontario, l'information sur la pourriture et les bois de rebut est résumée dans les tables sur les bois de rebut établies avant les années 1960. Ces données ont été récemment réexaminées et analysées et l'analyse a révélé des lacunes dans les données concernant la pourriture, plus particulièrement pour les peuplements surannés et les peuplements mixtes boréaux. De même, l'information sur la pourriture est mince en ce qui concerne les forêts de deuxième et troisième génération. Pour combler ces lacunes informationnelles, il faut une méthode opérationnelle pratique de collecte de données. Dans cette perspective, nous avons essayé deux instruments de détection de pourriture – la microsonde Sibert MicroProbe® [DmP] et le Résistographe F400 – pour déterminer leur pertinence pour les forêts de l'Ontario. À l'aide de ces instruments, mais aussi de la méthode d'évaluation visuelle classique, on a mesuré la pourriture interne à l'extrémité de coupe de billots de 71 érables à sucre (Acer saccharum Marsh.) et de 60 trembles (Populus tremuloides Michx.). La DmP et le Résistographe ont donné des résultats très différents de l'examen selon la méthode visuelle, quoique les écarts effectifs aient été faibles. La DmP s'est révélée plus rapide que le Résistographe pour le perçage des bois tendres, comme l'aspen, mais moins efficace pour le bois dur des érables. Bien que plus lent, le Résistographe offrait plus de possibilités, puisqu'il pouvait percer les bois tendres et les bois durs, s'étant révélé aussi suffisamment robuste pour nos conditions forestières. Une formation et de l'expérience sont nécessaires pour manipuler proprement les deux instruments et interpréter correctement les ensembles de données électroniques en résultant.

La DmP et le Résistographe détectent et quantifient la pourriture le long d'une seule ligne, dans l'arbre ou le billot. Des modèles d'estimation de la pourriture sont actuellement créés pour la conversion de ces données linéaires en estimations volumiques de la pourriture pour les arbres de l'échantillon à l'étude. On ne cesse de mettre au point des outils améliorés pour l'évaluation non destructive de la pourriture interne des arbres et des billots. Ces outils présentent de nombreux avantages par rapport aux systèmes de détection classiques : ils sont plus rapides; ils produisent une base de données électronique et permettent des réévaluations suivies des arbres pour surveiller la progression de la pourriture au fil du temps. Ces outils pourraient constituer un atout précieux à l'avenir pour les travaux de collecte de données sur la pourriture interne des arbres.

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Introduction

Wood decay is the most important disease in mature and overmature forest stands in Canada (Whitney et al. 1983). Indeed, decay is rated as more serious than fire with respect to wood volume losses (Van Sickle 1975). Decay is caused by microorganisms such as fungi and bacteria that break down the wood's cell walls, causing losses in wood fibre and reducing structural strength (Moody and Amirault 1992, Panshin and de Zeeuw 1970). In Ontario, an estimated 6 to 9 million cubic metres of standing timber are decayed annually (Gross 1985, Gross et al. 1992). These figures demonstrate the importance of decay in Ontario; however, broad, provincial timber loss estimates have limited use in forest management planning at the stand and management unit levels, which require species- and site-specific data, including estimates of decay.

Information on wood decay losses at the ecoregion, management unit, forest unit, and ultimately stand level would be valuable to many aspects of forest management. Reliable decay estimates help reduce uncertainty about future timber supply. In Ontario, the current transition to spatial wood supply modelling may require area-based or even stand/site-specific information inputs (M. Woods, 2002, Ont. Min. Nat. Resour., pers. comm.), including decay volume loss estimates. Decisions about building roads and scheduling harvesting operations depend on estimates of net volume obtainable from a given area of forested land, and decay losses need to be included in these estimates (Aho 1982, Basham 1991).

Acquiring and analyzing decay information is not new in Ontario. Prior to the 1950s, fairly arbitrary cull factors were assigned to each tree species based on timber scaling experience and observation (Basham 1991). To increase the reliability of these cull factors, small- and large-scale cull surveys that involved felling and sectioning thousands of trees to measure internal decay were conducted from the 1940s to the 1960s (Basham 1991, Whitney et al. 1983, Morawski et al.1958, White 1953). A large, province-wide cull study in the 1950s resulted in the production of provincial cull tables (Morawski et al. 1958). These past surveys indicated that although the amount of decay in living trees generally increases with age, decay is extremely variable across the landscape, both among and within host species, probably due to environmental variables.

The historical survey data used to create the provincial cull tables (Morawski et al. 1958) were recently re-analyzed in an effort to refine site-cull relationships (Foster and Harris 1999). This analysis revealed the weaknesses and large gaps in cull data in Ontario. For example, in the boreal forest, much of the data was collected in generally pure stands of jack pine (*Pinus banksiana* Lamb.), aspen (*Populus tremuloides* Michx), and black spruce (*Picea mariana* [Mill] B.S.P.). Little cull data was collected for other species, mixed stands, and older age classes (Foster and Harris 1999). What's more, when the data were stratified into smaller units such as provincial forest units[1] or ecosites[2], it became evident that the provincial cull tables have limited applicability at the site or stand level. Average decay trends can be deceptive, as the actual range of decay, even in 1 age class of 1 species, can be high (Morgan 1987). As Morawski et al. (1958) stated, the provincial cull tables can be used to roughly estimate decay volume by species for a particular site; however, local site conditions and other stand parameters may necessitate lowering or raising the estimates.

One of the most significant limitations of Morawski's cull tables is that they are based on only natural (i.e., fire-origin) stands. Stands created post-logging may not follow the same trends, and intensive forest management practices such as pre-commercial and commercial thinning may lead to significantly different cull patterns. Detecting these patterns early is critical to determining the real value of such intensive treatments.

[1] A forest unit is "an aggregation of forest stands for management purposes which have similar species composition, develop in a similar manner (both naturally and in response to silvicultural treatments), and are managed under the same silvicultural system" (OMNR 1996).

[2] Ecosites are based on identifiable and recurring patterns among vegetation types and soil types (Chambers et al. 1997). An ecosite is one of the hierarchical levels of ecological land classification, which is an "integrated ecological approach to surveying and classifying land and resources" (Lee et al. 1998).

Therefore, supplementary field data are necessary to localize the provincial cull factors and to address data gaps for decay in managed stands.

Although reliable estimates of decay volume losses are clearly needed, obtaining adequate sample data to calculate these losses at the site or stand level is difficult. Because stem decay is hidden and varies considerably within and among tree species, researchers have recommended felling and dissecting at least 30 trees in each age class in each stand to ensure reliable estimates of the extent of decay (Basham 1987). Since this type of survey is expensive and destructive, alternative data collection methods are being considered to detect and measure tree decay. For example, sample scaling of cut logs occurs in the northwestern, northeastern, and central regions of Ontario. The resulting database consists of scaling samples over a large area; cull factors, by species and management unit, are based on a 5-year rolling average of these scaling results (R. Maki 2000, Ont. Min. Nat. Resour. (retired), pers. comm.). This method produces a reliable estimate of cull for trees at a harvestable age at the management unit level; however, further sampling at the stand level is necessary to relate decay to site conditions, stand characteristics, or tree age.

Many instruments have been developed recently to measure decay in living trees. One of the first was the Shigometer, which uses electrical resistance to detect decay in trees (Shigo and Shigo 1974). Instruments that use ultrasound to test for decay in utility poles have been available since 1984 (Arita and Kuratani 1984). Other decay-detecting methods include wood hardness testers, decay-detecting drills, immunodiagnostic tests, and sonic stress wave analysis (Clausen and Green 1998, Garrett 1997, Bodig 1996, www.imlusa.com, www.sibtec.com). One of the main advantages of many of these decay detection methods is that sample trees do not need to be cut down; therefore, the same trees can be re-measured over time to track how the decay progresses. Each instrument and survey method has advantages and disadvantages; prospective users must assess overall applicability prior to choosing a tool.

To address the need for additional decay information in Ontario, we conducted a project using 2 decay-detecting instruments to asses their accuracy and applicability for collecting decay data in our forests.

Methods

The 2 decay-detecting instruments used in this project were the Sibert Digital MicroProbe (Sibert Technology Limited, Surrey, UK) and the Resistograph F400 (Instrumenta Mechanik Labor GmbH, Wiesloch, Germany). Detailed descriptions of these instruments are included in the Appendix. In general, both instruments measure and record the resistance encountered by a thin probe as it drills through wood. Resistance is less in decayed wood because fungi destroy wood structure, lowering wood density (Panshin and de Zeeuw 1970). Data are downloaded onto a personal computer and converted into graphs that show the tree's internal condition at the drilling point. The small holes created by the probes (1 to 3 mm in diameter) close quickly because of pressure from the weight of the tree and accumulation of sawdust.

To determine the accuracy of the instruments in detecting and quantifying decay, their use was compared with visually measuring decay in 60 aspen logs at St. Mary's Paper Company (Sault Ste. Marie, Ontario) and 71 sugar maple (*Acer saccharum* Marsh.) logs at the former Domtar hardwood sawmill (Domtar Wood Products, Sault Ste. Marie, Ontario). The instruments were also used in boreal mixedwood and tolerant hardwood stands to determine their operability under field conditions.

Measuring with the drills. Approximately 3 to 4 cm of wood from the end of each log was removed with a chainsaw to create a clean, fresh-cut surface. Each aspen log was drilled through its diameter with the Sibert Digital MicroProbe (DmP) and the Resistograph F400 (Resi), approximately 3 to 4 cm from the end of the log (Figure 1). Only the Resi was used on the maple logs because the thin probe of the DmP bent easily or broke in the hard wood (see Appendix). Drill entry and exit points were marked

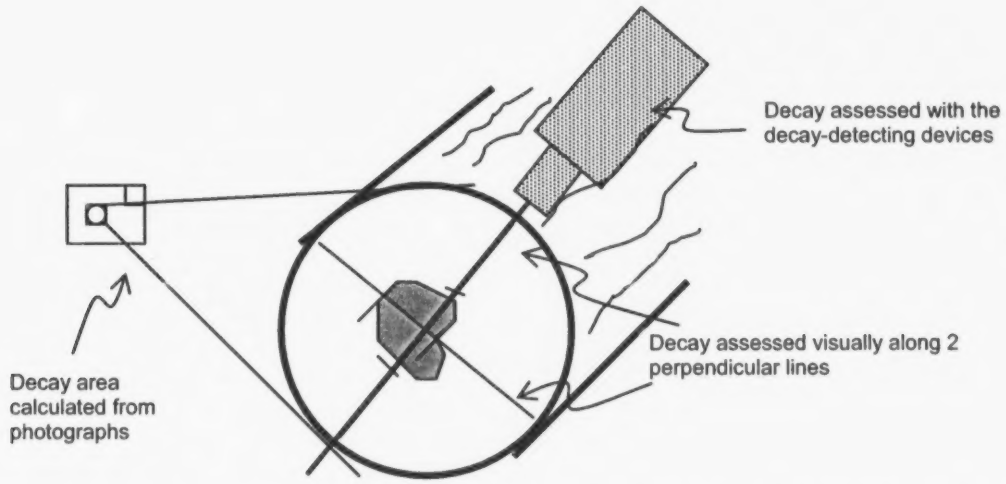
Decay assessed with the decay-detecting devices
Decay assessed visually along 2 perpendicular lines
Decay area calculated from photographs

Figure 1. *For each log, decay was measured visually and with the decay-detecting devices. A photograph was taken of the log end to measure decay area.*

on the cut surface. The resulting electronic data were used to determine the diameter of the decay column at the point of drilling.

Visual measurements. A line was drawn on the face of the cut log, between the drill entry and exit points, and defects along the line were measured with a ruler. Wood was also probed with a knife and fingernail to determine softness. Defects were recorded as stain (i.e., discoloured wood with no loss ot hardness) and decay (wood noticeably softer than sound wood). Because decay is usually irregular (i.e., not a symmetrical cylinder in the bole of the tree), it was also measured along a second line, drawn perpendicular to the first (Figure 1). These data were used to calculate a mean decay diameter for each log. For the 71 maple logs, a digital picture was taken of each cut surface. Arcview® (ESRI, Inc.) was used to calculate the area of decay from the photographs.

The paired t-test procedure (SAS Institute Inc. 1990) was used to compare diameter of decay measured by the decay-detecting drills with decay measured visually (Table 1). In addition, the mean decay diameter from 2 perpendicular lines per log was calculated and compared with a single decay diameter. For each maple log, the mean decay diameter was converted to a decay area estimate using the geometric formula πr^2. The paired t-test procedure was used to compare these decay area estimates with those calculated from the photographs. The power of the t-test in detecting a minimum detectable distance of 1 mm was estimated in all cases.

Table 1. *Decay assessment methods compared using a paired t-test procedure.*

Measurement 1		Measurement 2
decay diameter recorded by the DmP	vs.	decay diameter assessed visually
decay diameter recorded by the Resi	vs.	decay diameter assessed visually
decay diameter of single line through log	vs.	mean decay diameter of 2 perpendicular lines
decay area calculated using mean decay diameter	vs.	decay area calculated from photographs

Results

Decay in sugar maple logs. The diameter of decay recorded by the Resi was significantly different (at the 0.05 level) from that derived from the visual method ($p = 0.0200$) (Table 2). Although highly variable, the Resi detected, on average, 0.44 cm more decay than the visual method or 2.1% more of the total log diameter. The diameter of decay along 1 line did not differ significantly from the mean decay of 2 perpendicular diameters ($p = 0.1341$). However, decay area estimates calculated from the decay diameter data were significantly less than those calculated from the photographs. When calculated as a percentage of the total area of the cut log surface, the decay area estimated from the linear measurements averaged 2.9% less than the decay area calculated from the photographs. For the maple data, power analysis determined a 51 to 66% chance of detecting a true difference of 0.1 cm.

Decay in trembling aspen logs. Using a paired t-test, decay diameter recorded with the Resi was not significantly different from that determined by the visual method at the 0.05 level ($p = 0.1847$). The Resi recorded, on average, 0.34 cm less decay than was found using the visual method (0.9% of total log diameter), although variability was high (Table 2). In contrast, the diameter of decay detected by the DmP was significantly less than that measured visually ($p = 0.0261$). On average, the DmP detected 0.36 cm less decay than the visual method (2.3% of the total log diameter). Decay diameter of a single line was significantly greater than the mean of 2 perpendicular lines ($p = 0.0198$), although the mean difference between the 2 methods was only 0.23 cm. For the aspen data, power analysis indicated an 82 to 95% chance of detecting a difference of 0.1 cm (i.e., true differences are significantly different).

Table 2. *Comparison of decay data collected using the decay-detecting devices with that collected using the visual decay assessment method.*

Species and decay assessment method	Mean difference in amount of decay[1]	Mean difference as a percent of log diameter or area[2]	Range and standard deviation (*s*)	Pr > |t|[3]
Maple				
Resi vs. visual method	+0.44 cm	+2.1% of log diameter	+3.1 cm to -6.5 cm *s*=1.59	**0.0200**
1 line (visual) vs. mean 2 perpendicular lines	-0.65 cm	-0.76 % of log diameter	+6.1 cm to -7.2 cm *s*=3.61	0.1341
Area calculated from decay diameter data vs. area calculated from photograph	-16.36 cm^2	-2.9% of log area	+249.7cm^2 to -262.1 cm^2 *s*=54.17	**0.0003**
Aspen				
Resi vs. visual method	-0.34 cm	-0.9% of log diameter	+5.1 cm to -4.7 cm *s*=1.97	0.1847
DmP vs. visual method	-0.36 cm	-2.3% of log diameter	+3.8 cm to -3.5 cm *s*=1.23	**0.0261**
1 line (visual) vs. mean 2 perpendicular lines	+0.23	+1.6% of log diameter	+3.7 cm to -1.5 cm *s*=0.67	**0.0198**

[1] This column shows the mean difference in the amount of decay recorded by the first decay measurement method, compared with the second method. For example, for Maple, Resi vs visual method: the Resi recorded, on average, 0.44 cm more decay than was measured visually.

[2] This column shows the mean difference in the amount of decay recorded by the 2 different decay measurement methods as a percentage of the total diameter, or area of the log. For example, for Maple, Resi vs visual method: decay recorded by the Resi was 2.1% more of the total log diameter than was measured visually.

[3] p-values less than 0.05 are shown in **bold.**

Discussion

For the maple logs, decay data collected by the Resistograph F400S were significantly different from those collected using the traditional visual method, although the mean difference between methods was low (0.44 cm). The results suggest that for maple, the Resi overestimates the diameter of the decay column by approximately 2%. The general location of decay along the line was similar for both methods. For aspen, the difference between the Resi and the visual decay assessments was not significant. On average, the Resi underestimated the diameter of the decay column in aspen logs by only 1%. Similarly, Costello and Quarles (1999) found that the Resi accurately detected decay in blue gum (Eucalyptus globules) and Scotch elm (Ulmus glabra). The range and standard deviation values (Table 2) indicate high variability in the data collected visually and using the Resi.

In spite of the differences observed, measuring decay with the Resi is not necessarily less accurate than using the visual method. Several factors may have caused the differences between methods. First, the visual method and the Resi were not used at exactly the same location in the log. Although drilling occurred as close to the cut log end as possible, differences in the shape of the decay column can occur within 3 to 4 cm (i.e., the distance between the cut log surface and the point of drilling). This difference could be overcome by collecting the probe measurements prior to cutting off the end of the log. Then, the saw cut could be made at the point of drilling. Second, the drill probe tends to follow the path of least resistance as it progresses through wood (see Appendix B). Therefore, it occasionally deviated from a straight line resulting in a slightly different path than that of the visual method (this effect was even more noticeable with the DmP than the Resi). Third, errors invariably occurred when decay was measured visually. Although Basham (1987) maintained that one can quickly become proficient at visually estimating decay, he admitted that this method is highly subjective. Determining the exact transition point between stain and decay can be difficult and requires much experience for consistent and accurate results. Decay is defined as wood that is noticeably softer and weaker than sound wood (Basham 1991). However, incipient decay (the beginning stages) and sound wood, especially in normally soft wood such as aspen, may differ only slightly. The Resi mechanically detects and records differences in resistance to drilling (i.e., differences in wood hardness), thereby eliminating human error. Differences in wood hardness that were not detectable visually or manually using a knife to probe the wood may have been recorded by the Resi, although Bethge et al. (1996) and Costello and Quarles (1999) observed that the Resi did not detect discoloured wood or incipient decay.

In general, the Resi was easy to use in the field. Although somewhat heavy (5.3 kg), the instrument is sturdy and able to withstand transport through rough field conditions. The electronic data capture unit is incorporated into the drilling instrument, thereby eliminating the need for an external data logger. Although the Resi is designed to use "clip-on" rechargeable batteries, it was easily converted to use 12V dry cell rechargeable batteries, which greatly increased the amount of work the drill could perform each day. Although mechanical problems occurred, appropriate adjustments could usually be made in the field. Annual servicing by a qualified technician was necessary, and several moving parts within the drilling unit needed to be replaced after 2 years of heavy use in the hard wood of sugar maple trees.

The Digital MicroProbe recorded a smaller decay diameter than the visual method in the aspen logs (mean difference = 0.36 cm). The results suggest that for aspen, the DmP underestimates decay by approximately 2%. Again, the range and standard deviation values (Table 2) do indicate a great deal of variability between data collected by the DmP and that collected by measuring visually.

Similar caveats to those mentioned above for the Resi must be applied to the DmP, first concerning the distance between the visual and mechanical decay assessments (3 to 4 cm) and second, concerning the subjectivity of the visual method. For aspen, visually determining exactly where decayed and sound wood begin and end can be difficult, even when the wood is probed with a knife, because even healthy aspen is fairly soft. Therefore, as with the Resi, the DmP may be more accurate than a visual estimate in detecting this demarcation. The path of the DmP probe

through the diameter of the log often deviated from a straight line (see Appendix A), thus resulting in a slightly different decay profile than the visual method. One of the drawbacks of the DmP was the flexibility of the thin (1 mm) probes. These probes bent or broke easily, especially when drilling through hard wood such as sugar maple. The sturdier probes of the Resi (1.5 to 3 mm) were more apt to drill through the log in a straight line.

One of the main advantages of the DmP is its speed. Whereas the Resi must be drilled into and out of the tree at a constant drilling speed, the speed of the DmP relies on the density of the wood. In less dense wood, such as aspen, the drill penetrates very quickly. Once a tree has been measured, it takes only a few seconds to pull the probe out of the wood. The DmP is lighter than the Resi (2.3 kg) but it needs an external data logger (we used the Psion Workabout® [Psion PLC, London, UK]), and the external rechargeable battery pack drained quickly when used in hard wood such as sugar maple. When fully assembled, the thin probe and its cover (see Appendix A) were prone to damage when traveling in rough field conditions.

Decay often forms in the shape of a cylinder with tapering ends within the bole of the tree. However, the shape of the decay cylinder, or column, is not always symmetrical, and many small columns can develop in the same tree (Figure 1). Thus, increasing the number of lineal measurements taken through the wood should increase our ability to estimate the actual diameter of the decay column. For maple, the diameter of the decay along 1 line was not significantly different than the mean of 2 perpendicular diameters, indicating that the shape of the decay column in the maple logs was usually centred and somewhat symmetrical. For aspen, the mean of 2 perpendicular diameters was significantly different from that of 1 diameter, suggesting that the decay columns in the aspen logs were less symmetrical than those in the maple. Each tree species may require a different number of linear decay measurements to calculate an acceptable mean decay diameter.

When compared with decay area calculated from the photographs, converting data from 2 perpendicular diameters into a decay area measurement significantly underestimated decay area (approximately 3% of the total log surface area). Even small irregularities in the shape of the decay column, which would be included in the area estimate from the photos, may have been missed by the linear measurements (Figure 2). However, visually measuring cull area from the photographs also had limitations. The decay area was calculated by delineating changes in colour and texture on the photographs. Panshin and de Zeeuw (1970) state that the early stages of decay may not produce readily recognizable changes in colour; thus, human error is highly likely when interpreting the photographs.

Application. A linear measurement of decay in a tree or log, or even an estimate of decay area

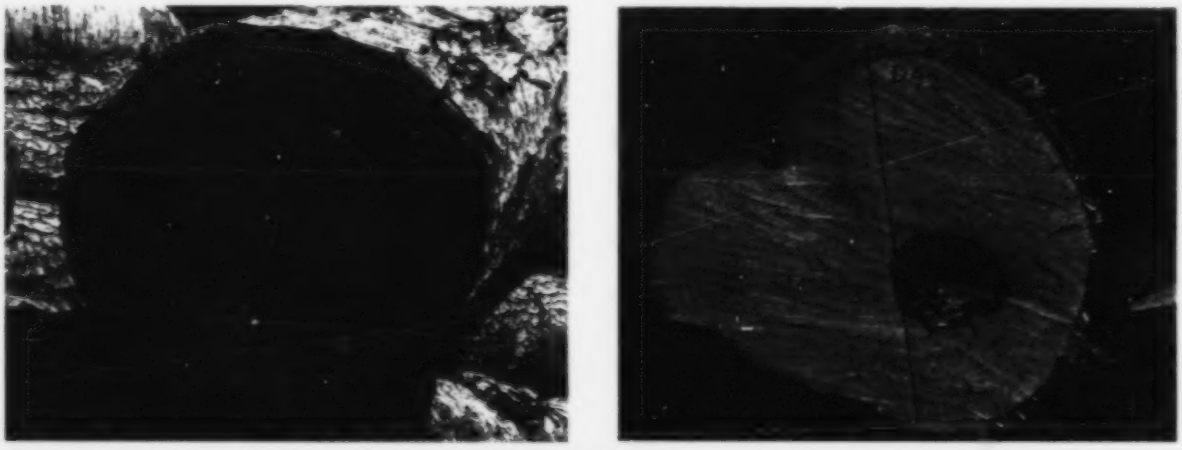

Figure 2. *The decay column in the aspen and maple logs was not always symmetrical (left). In some logs, the decay was off centre (right); therefore, measuring along a single line could under- or over-estimate decay area.*

at a specific point in the tree, is not very useful for timber supply analyses that require estimates of percent gross merchantable volume lost to decay. In British Columbia, historical cull survey data were used to create models that convert a single decay area measurement per tree into a decay volume estimate (LeMay 1992). Similarly, we are creating decay volume estimation models for Ontario using the original Morawski cull survey data (S. Greifenhagen and M. Cherry, unpubl). Initial models have been constructed for hard maple and aspen in northeastern Ontario. Further data management and analyses are necessary to refine the models for all major wood-producing tree species in Ontario. Ultimately, a survey system that uses a non-destructive decay-detecting instrument such as the DmP or the Resi, in conjunction with the volume estimation models, will allow rapid estimation of decay volume in a stand or larger area.

Because the extent of decay can vary widely among individual trees, even within even-aged stands on uniform sites, the accuracy and reliability of the data generally increase with the number of sample trees (Zillgitt and Gevorkiantz 1946). Using the decay-detecting instruments eliminates the need for cutting and sectioning trees; therefore, a larger sample size can be measured in less time with less cost, and without destroying the trees. The DmP is clearly the fastest for measuring decay in conifers and intolerant hardwoods. However, the relative sturdiness of the Resi probe and the constant drilling speed both in and out of the tree allow it to work well in hard woods such as sugar maple as well as in soft woods. Further testing in other tree species, especially conifers, is necessary to determine the best application for each instrument.

Estimating tree decay using either the Sibert DmP or the Resistograph F400 involves several steps and calculations. Each step in the process, from initial drilling to a final volume estimate, has a level of error associated with it, producing compounded error in the final results that may or may not be acceptable for specific tasks, such as producing decay factors for wood supply modelling or assessing the storability of overmature forest stands. Decay volume estimates developed from data collected with these instruments may have large confidence intervals. Visually estimating decay using external signs (e.g., conks, seams, etc.), however, may have a higher risk of human bias and error. An acceptable level of uncertainty in the results must be determined by the end user of the data prior to choosing a survey method.

The Resi and the DmP demonstrate the progress that has been made in decay assessment techniques. These devices make very small holes in trees that do not increase the risk of decay; examination of trees 10 years after repeated drillings by the Resi showed that decay fungi did not enter into the tree through the resulting holes (Weber and Mattheck 2005). They automatically create an electronic database and do not require sectioning of the tree; therefore, repeated measurements over time are possible. However, the field of non-destructive evaluation of wood is still in its infancy and new instruments are continually being developed (Bodig 2001, Nicolotti and Miglietta 1998). For example, the Picus (Argus Electronics GmbH, Rostock, Germany) is a 3-dimensional sonic tomograph that takes multiple decay measurements from multiple sensors on a tree. Using the data collected by the tomograph and specialized software, 2- and 3-dimensional pictures of the internal quality of the tree are constructed, and decay area and/or volume are calculated (Gilbert and Smiley 2004). These advances should lead to simpler and faster non-destructive methods for detecting decay in living trees.

Volume losses to stem decay are difficult to quantify accurately or to value, partly because of the hidden, internal nature of decay and the unreliability of external indicators (Basham 1991, Singh 1993). Because of its hidden nature and the high local variability in presence and extent, decay prediction remains one of the most difficult aspects of provincial inventory and growth and yield programs (BCMF 1999). New decay-assessment techniques that use recently developed electronic decay-detecting instruments and decay volume-estimation models can fill existing data gaps, including those related to decay in second- and third-generation stands growing under various management regimes, in mature and over-mature stands, and in mixedwood stands.

Next steps. The instruments must be further tested on softwoods, including pines and spruce, to determine their applicability in Ontario's forests. As well, decay volume estimation models need to be developed for all commercial tree species in Ontario.

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Appendix A. Description of the Sibert Digital Microprobe

The Sibert digital microprobe (DmP) (Sibert Technology Limited, Surrey, England) has a thin probe, approximately 1 mm in diameter, that is drilled into a standing tree, log, or cut timber at a rate of 7000 revolutions per minute (Figure 1). The DmP detects differences in the wood's resistance to the advancing probe (for example, resistance is less in decayed wood or cavities) and records the data digitally. For each 0.1 mm that the probe moves forward through the wood, the microprocessor collects 1) the distance drilled to that point, 2) the number of revolutions of the probe since the last 0.1 mm, and 3) the force applied to the probe at that point. The data is transmitted in ASCII format through an RS232 serial port to a handheld data recorder. Once the data is downloaded onto a personal computer, the DmP software converts these ASCII files to Microsoft Excel files. For each drilling, a graph is created that depicts drilling force (upper line) and wood hardness (lower line) (Figure 2). Reductions in these 2 lines indicate decay is present.

The manufacturers of the DmP maintain that little training or experience is needed to operate the drill or analyze the data. However we have found that training is needed to operate the drill consistently. Garrett (1997) also found that a knowledgeable operator was necessary. Data analysis can be difficult and open to interpretation; therefore, experience is essential. Cavities and pockets of advanced decay are usually easy to determine from the graphs, whereas incipient decay (early stages) may be impossible to determine accurately.

Advantages of the DmP

The DmP is lightweight and portable and uses long-life rechargeable batteries. When fully charged, the battery can support about 100 drillings through soft woods such as trembling aspen (*Populus tremuloides* Michx). The probe drills rapidly through soft woods (a maximum of 10-15 seconds to drill through an aspen stem) and leaves a hole that is less than 1 mm in diameter. A permanent, electronic database is created on site and can be converted into a spreadsheet. Since the sample tree does not need to be felled, repeated measurements can be taken to assess decay progression over time. The DmP can detect hidden decay when outward signs or symptoms are not visible.

Disadvantages of the DmP

Use of the DmP is limited by the battery pack. Drilling harder wood takes longer and therefore uses more power. We found that about 9 drillings through sugar maple (*Acer saccharum* Marsh.) with a diameter of 30-40 cm drained the battery. Because the DmP relies on battery power, the instrument does not work well in very wet conditions or in temperatures below 0°C. The operator must push the probe against the tree at a constant pressure throughout the drilling

Figure 1. *The DmP being used in a trembling aspen stand in Manitouwadge, Ontario. Data are recorded on a handheld data logger.*

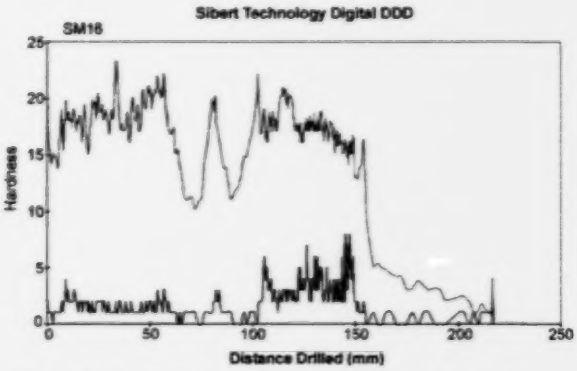

Figure 2. *An example of the graphical output from the DmP software. Declines in both the drilling force (upper line) and hardness (lower line) indicate decay. Location and extent of decay can be determined on the scale.*

procedure. Maintaining a constant pressure can be difficult when cavities and decay are encountered.

As the probe rotates through the tree, it tends to follow the path of least resistance. Therefore, the path of the probe may deviate from a straight line at the transition between decayed wood and sound wood or even at the transition between early and late wood in growth rings. The thin probes are also very prone to bending and breaking, especially in harder wood such as maple, and can be difficult to pull out of harder wood.

Because the DmP assesses wood quality only along one transect through the tree, the possibility of missing off-centre pockets of decay is high. Repeated measurements at varying angles may be necessary to detect these pockets. Although the DmP is lightweight and easy to carry, care must be taken to prevent damage to the probe and the probe cover while travelling over rough terrain. The electrical cords that attach the DmP to the battery and the data logger often get tangled in shrubs and other debris while the operator is walking through a forest stand. Finally, the initial cost of the DmP is substantial (CDN $9,000.00 [1]), a data logger is required, and probes must be replaced when bent or broken.

[1] Source: Sibert Technology Limited website: www.sibtec.com (accessed March 2005).

Appendix B. Description of the Resistograph F400

The Resistograph F400 (Resi) (Instrumenta Mechanik Labor GmbH, Wiesloch, Germany) operates on the same principle as the DmP in that decay is detected as a change in resistance to drilling force. A fine probe (3 mm in diameter at the tip) is drilled into the wood at approximately 1,000 revolutions per minute (Figure 3). The amount of power needed to drill through the wood is measured electronically as a value of drill resistance relative to penetration depth. The Resi produces a paper graph of this data as the drilling occurs. The data are also stored electronically in the unit itself. Files are downloaded from the Resi onto a personal computer using the included software. The resulting graphs require some experience to interpret (Figure 4). Users must be familiar with wood resistance patterns for each species to accurately interpret decay presence or absence (Costello and Quarles 1999). As with the DmP, cavities and advanced decay are easier to interpret than incipient (very early) decay.

Advantages of the Resi

The Resi F400 is sturdy and easy to handle. Rechargeable clip-on batteries are sufficient for a small number of drillings, and an adapter cable connects the Resi to a larger power source such as a 12V rechargeable dry cell battery for longer-lasting drilling power. The drill speed is constant and does not depend on pressure applied by the operator. A data logger is not necessary, as the electronic data files are stored directly in the Resi unit, and the paper graphing capability allows for quick on-site decisionmaking. The thickness of the drilling probe (1.5-3 mm) reduces bending and breaking. As with the DmP, the Resi detects hidden decay that has no associated outward signs or symptoms and allows repeated measurements to be taken to assess decay progress over time in a single tree.

Disadvantages of the Resi

Although the Resi drills through soft woods such as trembling aspen faster than denser woods such as maple (the drill has 2 settings, one for hard wood, and one for soft wood), its constant drilling speed results in a longer drilling time than the DmP. Also, the user can pull the DmP probe out of the tree in a few seconds when the measurement is complete, but he or she must drill the Resi out in reverse. These factors result in longer total drilling time for the Resi (7-100 cm per minute, depending on wood density). The clutch assembly of the Resi is prone to wear and breakdowns. The drilling probes quickly become dull in denser wood and must be replaced often. In addition the Resi probe tends to deviate from a straight drilling line when pockets of decay are encountered, although this deviation is not as pronounced as with the DmP.

Annual servicing is expensive because of high shipping costs (servicing is done in Atlanta, Georgia). The Resi is heavier than the DmP (5.3 kg vs. 2.3 kg), and any extra batteries greatly increase the weight of field equipment. Finally, the initial cost of the Resi is substantial (CDN $8,200.00 [1]), and extra probes and batteries are needed over time.

[1] Source: IML Inc. website: www.imlusa.com (accessed March 2005).

Figure 3. *The Resi F400 being used on a sugar maple in the Algoma region of Ontario.*

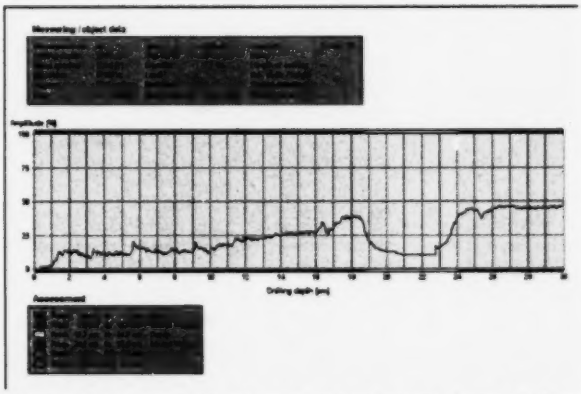

Figure 4. *An example of the graphical output from the Ftools software. A dip in the graph indicates decay. Location and diameter of decay can be read from the graph.*

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